Characteristics of Future Aviation Fuels

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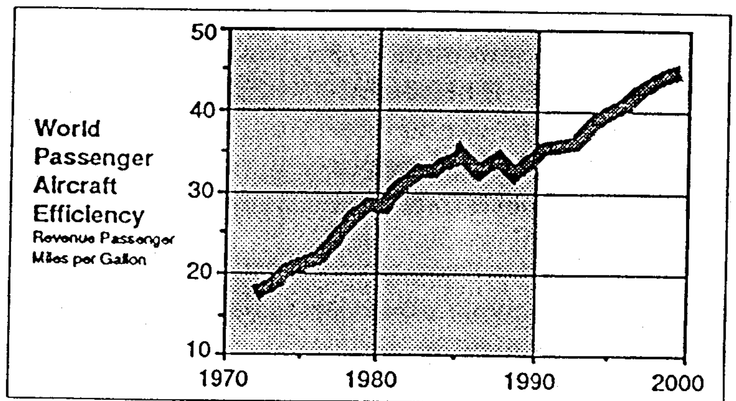
Which Fuel? This is a question that surfaces every time there is a supply and price scare associated with crude oil. Up to now, each flurry of activity has subsided after the panic ended and legislators realized that no alternative fuel proved to be more affordable or available than those from petroleum. Now there is an increasing number of environmental concerns, such as global warming, driving the search for the replacement of petroleum-based fuels. However, studies indicate that the currently used aviation fuel is as likely to satisfy these concerns as the few alternative fuels that are suitable for use in aircraft. Hydrogen, publicized as the most environmentally benign alternative to petroleum, will become economically acceptable only after the world has exhausted its fossil fuel resources or a low-cost, abundantly available source of electric power, such as nuclear fusion, is developed.

Improving efficiency will be the principal way to lessen the impact of aircraft on the environment until a technically and economically practical non-fossil-based fuel is discovered. Improving efficiency has always been and will continue to be a primary objective of aircraft operators and manufacturers.



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Supply

Until recently the number of years crude oil reserves were expected to support the current consumption rate varied very little from year to year. Each year, the oil consumed was shown to be replaced by the addition of new reserves, primarily in the Middle East. Because these estimates indicate no margin for growth and reserve additions are primarily in an unstable area of the world, these numbers are often used to substantiate outlooks showing near-term problems with crude oil availability along with greatly inflated crude oil prices, and hence a need to develop alternative fuels. However, the use of such data for this purpose is deceptive because:

Published in Transportation and Global Climate Change, American Council for an Energy-Efficient Economy, Berkeley, (1993).

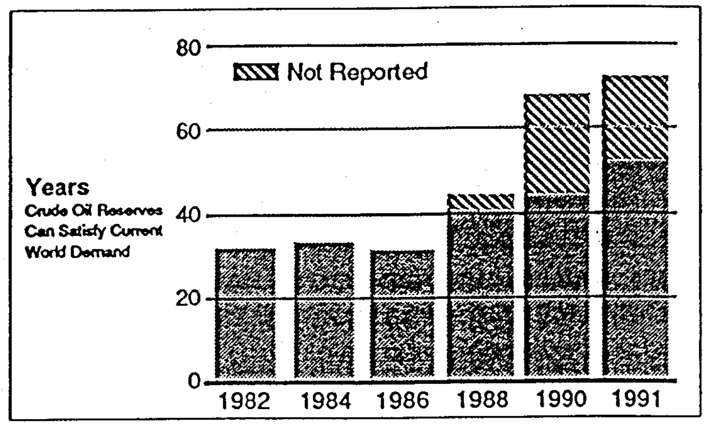
- "Proved reserves" reflect crude oil availability restrictively defined by technical and economic conditions — they are not an absolute, or even commercial development, limit.

- "Proved reserves" assume no new technology beyond that in an advanced stage of development at the time of estimate.

- Incentives for reporting new discoveries have been greatly reduced by unyielding and often unreasonable attacks on their development by a variety of special interest groups.

> Proved reserves are generally taken to be those quantities which geological and engineering information indicate with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions.
> Reference: BP Statistical Review of World Energy (June 1991).

During the early 1980s oil exploration activity stimulated by expectations of ever increasing prices boosted estimates of crude oil reserves, even within the restrictive definition of "proved reserves." If the definition is revised to include oil likely to be recovered at a cost of less than $20 per barrel, there is sufficient crude oil to last well into the next century. This more optimistic, and realistic, view of oil has pushed availability arguments for developing alternative fuels into the background; thus the current rallying point is the environment.



Reserves of petroleum at ≤ $20 per barrel are sufficient to last well into the next century.

There is a growing realization among environmentalists that an energy source that could replace a significant amount of coal or petroleum must have abundant reserves. Therefore, natural gas has become increasingly popular as the clean fuel of the future. There is little agreement, however, as to the magnitude of natural gas reserves. Reserves reported for conventional gas in the United States (approximately 4% of the world total) appear to be about the same as crude oil in terms of availability at the current price and rate of production.[1] Estimates of recoverable gas from unconventional sources such as coal seams, tight sands, and Devonian shale vary from almost none to several times more than that available in the form of conventional gas. Estimates for methane hydrates are in the category of thousands of years — but many scientists dispute the geological hypothesis for its formation, and hence there is still some question as to the exist-

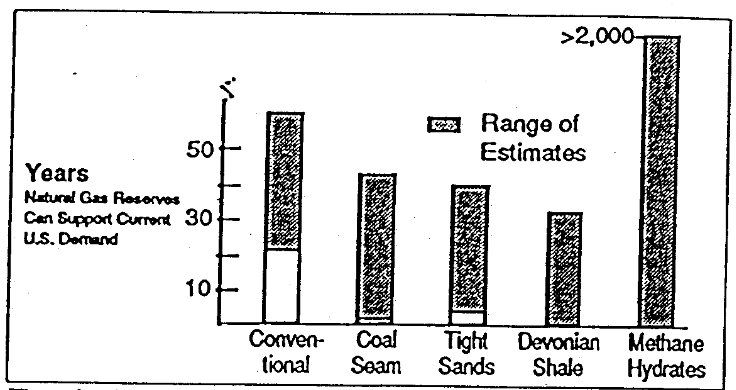
> Conventional gas is defined as that which is contained as a gas phase or in solution with crude oil in natural underground reservoirs.

[1] Editor, "BP Review of World Gas," The British Petroleum Co. (August 1991).

ence of such massive quantities of gas.[2,3]

Conventional Fuels

During the past two decades environmental considerations have had an increasing impact on both personal and business activities. Until recently, environmental problems have been treated as local issues, principally identified with large urban areas. Now a concern has developed that is of a more global nature. This concern is the "greenhouse" effect — a global warming caused by the introduction of infrared-radiation-absorbing gases into the earth's atmosphere. These gases include carbon dioxide (CO_2), the chlorofluorocarbons (CFCs), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Of these, the most prevalent and publicly recognizable is CO_2. There is little question that a higher demand for fossil fuels will increase the production of CO_2. Therefore, the obvious solution to global warming is to limit or reverse this growth through conservation or substitution of non-fossil sources of energy. Unfortunately, the social, economic, political, and technical problems associated with accomplishing this are enormous. For example:



There is plenty of natural gas, but how much is low-cost conventional?

- Many nations are planning to use more coal to boost their standard of living, particularly the countries of South and East Asia. These plans are not likely to be reversed.

- Nuclear power is the only non-fossil energy source with a real potential for replacing significant quantities of fossil fuels. The current worldwide trend is to back away from nuclear power, and this industry is not likely to recover in the near future.

- The world's population is increasing at such a rate that steps to improve energy efficiency are counteracted by increases in the number of energy users. Past attempts to limit population growth have had limited success.

Therefore, those worried about global warming are having a difficult time identifying projects that can produce reportable results in a reasonable time. This situation can lead

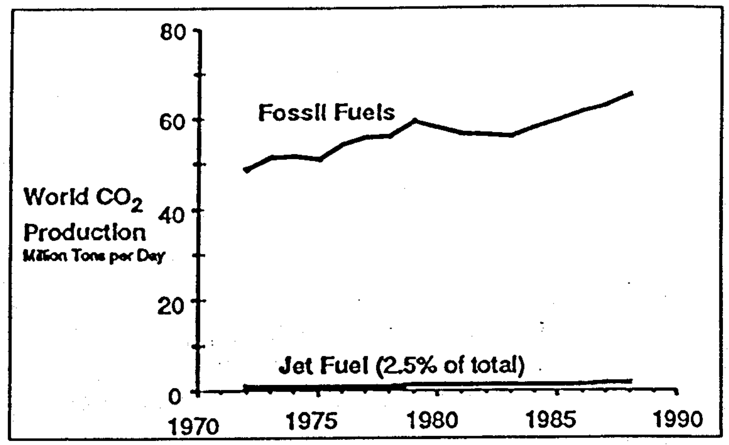
[2] A.G.A. Gas Supply Committee, "The Gas Energy Supply Outlook: 1980-2000," American Gas Association, A.G.A. #F00728 (October 1980).

[3] A.G.A. Gas Supply Committee, "The Gas Energy Supply Outlook: 1989-2010," American Gas Association, A.G.A. #F00889 (September 1989).

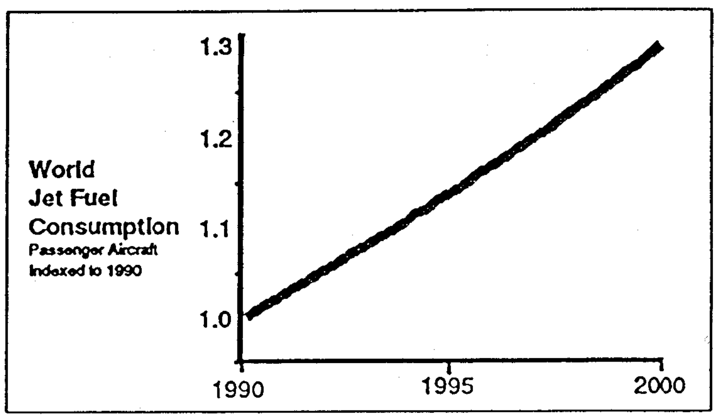
to actions that are not necessarily justified on the basis of technical or economic merit.

Aviation is not a major producer of carbon dioxide. Aircraft consume about 2.5% of the fossil fuel used. However, aviation is one of the few petroleum users projected to have a continuing growth in fuel consumption. During the past twenty years, the CO_2 produced by the growth in aviation has been somewhat offset by improvements in aircraft efficiency. Aggressive programs to improve the efficiency of aircraft will continue in the future. Improving efficiency will be the most cost-effective and technically feasible method for reducing aircraft-generated CO_2 until an affordable non-fossil-based alternative fuel is developed.

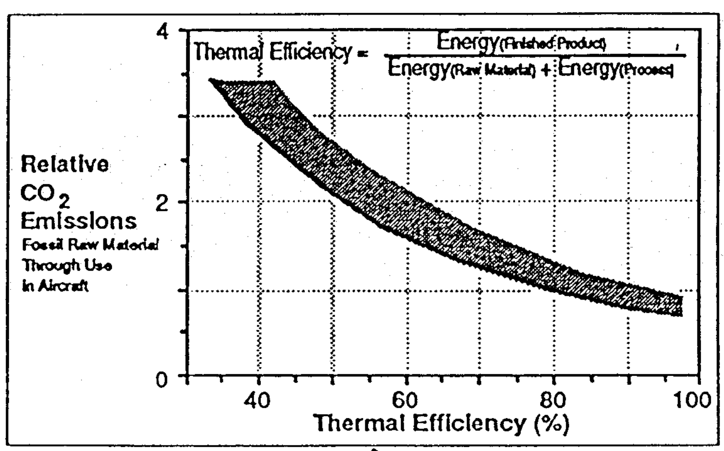
A major shortcoming in regulations designed to solve environmental problems, is that analyses required to identify negative aspects of the proposed action are often neglected. Each processing step used to upgrade or modify a raw material uses energy. If this energy is from a fossil fuel, the CO_2 produced in the transformation will increase as the thermal (conversion) efficiency decreases. Therefore, regulations that increase the fuel processing requirement also increase the CO_2 produced per unit of usable end-product energy.



Aircraft account for a very small fraction of the world's production of CO_2.



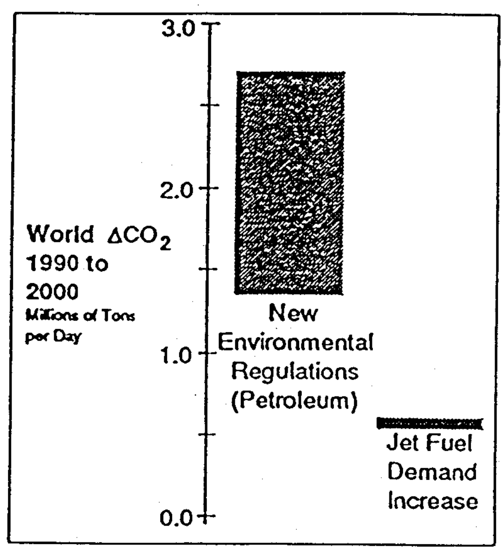
Jet fuel consumption is forecast to grow at a moderate rate during the next decade.



Regulations that result in more fuel processing will increase the amount of CO_2 produced per unit of usable energy.

The most notable environmental action related to transportation that will drop fuel production efficiency (ε), and hence increase overall CO_2, is the substitution of methanol manufactured from natural gas for gasoline from petroleum ($\varepsilon < 70\%$[4] versus $\varepsilon > 90\%$). However, it is the less advertised actions requiring changes to the composition of fuel that are likely to cause the biggest overall drop in fuel production efficiency. These include:

- Lower diesel and gas oil sulphur (≤0.05 wt.%) and aromatic content (≤20 vol.%).
- Lower gasoline aromatics (≤1.0 vol.% benzene; ≤25 vol.% total).
- Increased U.S. gasoline oxygen content (11 vol.% as Methyl Tertiary Butyl Ether (MTBE)) — this is now being recognized as a source of increased CO_2.[5]
- A worldwide product demand shift — less residual (heavy fuel oil), more product upgrading.



The CO_2 added to the atmosphere by the growth in aviation will be small relative to that resulting from new regulations.

It is becoming more evident that there are likely to be sources of regulation-caused CO_2 that have not been identified, much less quantified. However, regulations that have already been passed will add more CO_2 to the atmosphere than that from projected increases in the consumption of jet fuel. The largest drop in efficiency outside the United States will be from the increased use of hydrogen to reduce the sulphur content of diesel and gas oil.[6,7] A drop in the efficiency of U.S. refineries also involves an increased use of hydrogen to saturate aromatics plus the requirement for an oxygenate additive, such as MTBE in gasoline (the energy used to produce hydrogen and additives is a charge against refinery efficiency).[8]

Although current regulations governing the composition of fuels apply only to diesel and gas oil, they are likely to indirectly cause a lowering of the sulphur and aromatic

[4] J. R. LeBlanc and J. M. Rovner, "Remote gas conversion in worldscale methanol plant," Hydrocarbon Processing (March 1990).

[5] P. Morton, "An Industry Going Nowhere," Oilweek (July 15, 1991).

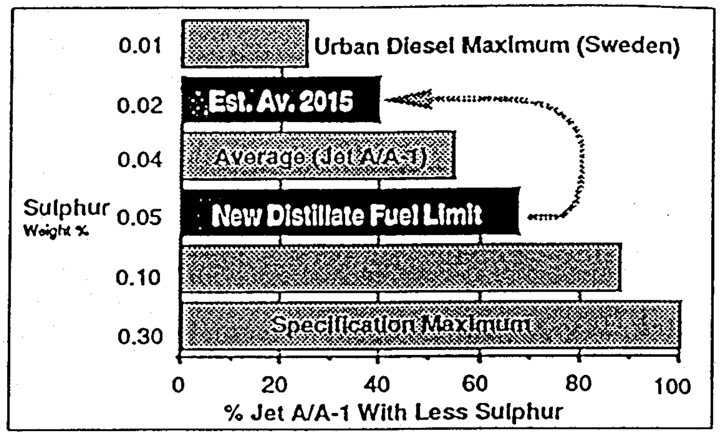
[6] L. White, "Sulphur Dioxide Emissions from Oil Refineries and Combustion of Oil Products in Western Europe (1989)," CONCAWE Air Quality Management Group, Brussels (April 1991).

[7] D. J. O'Brien, "Global and Regional Trends in Investment Implications for the Oil Industry," Proceedings of the 2nd Jakarta International Energy Conference '91," Jakarta (October 1991).

[8] R. C. Scherr, G. A. Smalley Jr. and M. E. Norman, "Clean Air Act Complicates Refinery Planning," Oil & Gas Journal (May 27, 1991).

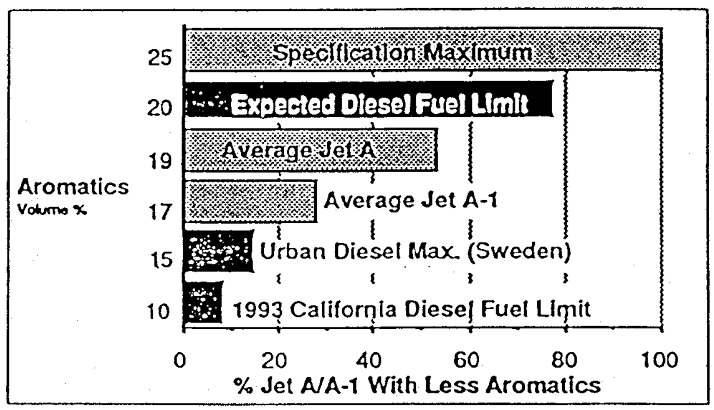
content of jet fuel. This is partly because product marketing requirements will not allow a total segregation of diesel, jet fuel, and gas oil.

Boeing data show that the average sulphur content of 90% of currently delivered jet fuel is below 0.1 wt.%.[9] This has resulted in an average jet fuel sulphur content (0.04 wt. %) that is about an order of magnitude lower than the 0.3 wt. % specification maximum. Analyses of jet fuel samples from refineries that would be able to satisfy projected year 2015 product demand and composition requirements indicate that the average jet fuel sulphur content is likely to drop to 0.02 wt. %.



New restrictions on the sulphur content of fuels, particularly diesel, will indirectly cause a reduction in the sulphur content of jet fuel.

Aromatics are believed to be a primary cause of particulate emissions in diesels. Therefore, both federal and state regulations controlling the aromatic content of diesel fuel have been passed. The most stringent of these is a California regulation that limits its aromatic content to 10 vol. % by 1993.[10] Even though California tends to lead the world in fuel-related regulations, few countries could afford the costs associated with such a severe diesel fuel restriction. Unless a clear benefit is demonstrated for an aromatics reduction to 10 vol. %, a more likely restriction for worldwide diesel fuel is 20 vol. %.



A forced reduction in the aromatic content of diesel is likely to result in a reduction in the aromatic content of jet fuel.

There are no plans to require a reduction in the aromatic content of jet fuel. However, any reduction in the aromatic content of diesel is likely to result in a reduction in the aromatic content of the total distillate pool. If the worldwide aromatics limit for diesel is

[9] O. J. Hadaller and A. M. Momenthy, "The Characteristics of Future Fuels — Part I," Boeing Document D6-54940 (August 1989).

[10] F. Stodolsky, "Energy and the Clean Air Act," Energy Matters, TRB Committee on Energy and Travel Demand, Vol. 1, No. 2 (December 1990).

forced to be 20 vol. %, a refiner's need to maintain flexibility in the marketing of distillate fuels is likely to force the average aromatic content of jet fuel to less than 15%. A reduction in the aromatic content of jet fuel would result in a fuel that is cleaner burning (lower radiation) and has a higher energy per unit weight. Unfortunately, it also means a lower density and lower energy per unit volume.

The search for an abundant-clean fuel has revived various concepts for replacing transportation fuels derived from crude oil. Until recently, liquid methane was the only natural-gas-derived fuel considered satisfactory for aircraft. Recently, processes have been developed that allow the manufacture of conventional jet fuel from natural gas.[11] Of particular interest to aviation is that several of these processes that have reached the demonstration plant stage of development produce distillate fuels (including jet fuel).[12, 13] The jet fuel from such processes has low to no sulphur or aromatics.

Alternatives

A fundamental requirement for a commercial aircraft jet fuel is that it have:

- A heat of combustion per unit mass sufficiently high to allow the transport of revenue producing payload — not just mission fuel.
- A heat of combustion per unit volume sufficiently high to allow the storage of fuel without compromising aircraft design or performance.

	Net Heat of Combustion		Boiling Point
	Btu/lb	Btu/Gallon	°F @ 1 atm
Conventional	18,400 to 19,000	116,000 to 127,000	>100
Hydrogen	51,500	29,675	-423.2
Methane	21,500	76,193	-258.7
Propane	19,774	96,121	-43.7
n-Butane	19,506	97,973	31.1
Ethanol	11,550	76,000	172.9
Methanol	8,640	57,370	148.5

It is very difficult to quantify "sufficient" in terms of either mass or volumetric heat of combustion. However, these properties for conventional jet fuel (kerosene) rarely cause an aircraft design compromise or prevent the consideration of a mission. On the other hand, the volumetric heat of combustion for liquid hydrogen is so poor that it would force design compromises even if it were not a cryogen. Design compromises associated with liquid methane (e.g., fuel in the body) are primarily related to the fact that it is a cryogen.

The liquefied petroleum gases, propane and butane, have been proposed as alternative fuels for aircraft.[14] These fuels are not cryogens, but they have many of the storage and transfer problems associated with a cryogen. In-depth studies of these fuels have not

[11] M. Quinlan,"Competition from Gas," Petroleum Economist (January 1991).

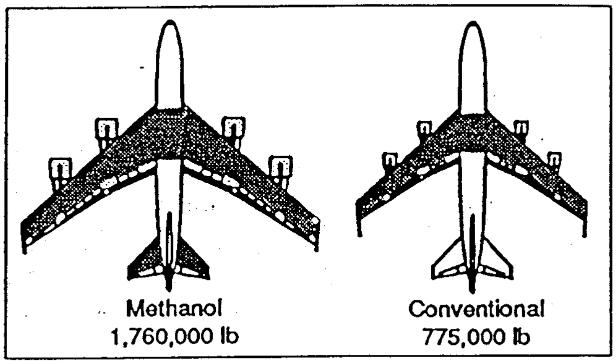
[12] A. L. Velocci, Jr., "Creating Liquid Fuels from Natural Gas," The Lamp, Vol. 73, No. 3, Exxon Corp. (Fall 1991).

[13] M. van der Burgt, et al.,"The Shell Middle Distillate Synthesis Process," Shell International Petroleum Co., London (November 1989).

[14] Editor, "U.S.S.R. Pushes CNG, LNG as Motor Fuel," Oil & Gas Journal (May 6, 1991).

been conducted because the natural supply is not sufficient to support a world aviation fleet. Manufacturing propane and butane offer no availability, cost, or environmental advantages as replacements for conventional jet fuels.

The alcohols, methanol and ethanol, have such poor mass and volumetric heats of combustion that they would not be satisfactory commercial aircraft fuels. They are important to the aircraft industry only because their widespread production and use would influence the properties, supply, and cost of conventional jet fuels.

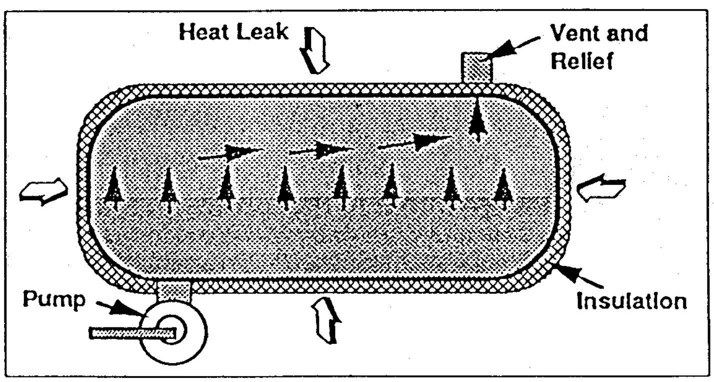


Alcohol-fueled aircraft would be very large, heavy, and inefficient.

Therefore, only the cryogens, methane and hydrogen, have sufficient positive attributes to justify serious attention as possible replacements for kerosene-type aircraft fuel.[15] In addition, they are perceived by environmentalists to be clean fuels, particularly hydrogen.

Cryogenic fuels cannot be handled by a conventional aircraft fuel system. The use of cryogens will require the development of new technology, or significant improvements in existing technology, before an aircraft that satisfies realistic commercial requirements can be designed.[16] The normal boiling points of hydrogen and methane are considerably below the lowest ambient temperature. This means that the aircraft fuel system must be:

- Thermally insulated from the environment and primary aircraft structure.
- Cooled to the liquid saturation temperature prior to or during the initial stages of tank loading or fuel transfer.



The storage and transfer of cryogens in aircraft involve the interaction of complex thermodynamic and fluid dynamic processes.

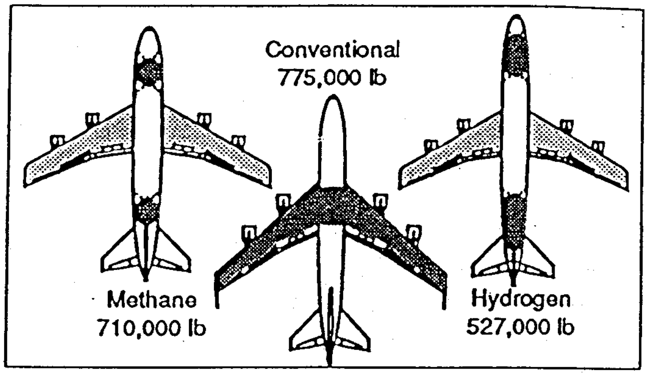
The fuel tanks of aircraft using cryogens must be insulated pressure vessels. In comparison to other fuel tanks they would be very large in terms of energy stored. These tanks would have to be located in the fuselage in-

[15] Deutsche Presse-Agentur, "Cleaner Jet Burns Hydrogen in Engine," Seattle Times (May 21, 1990).

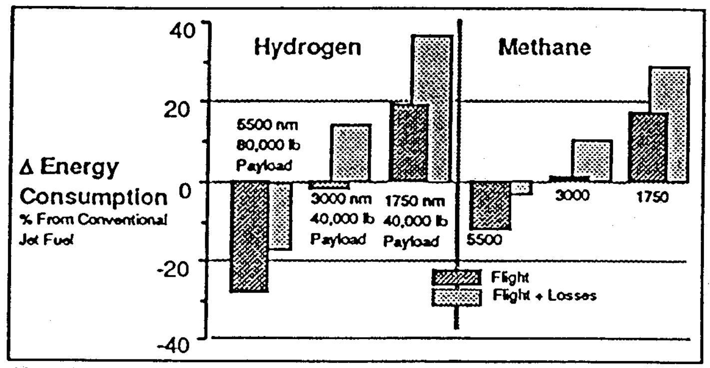
[16] A. M. Momenthy, "Fuel Subsystems for LH_2 Aircraft: R & D Requirements," International Journal of Hydrogen Energy, Vol. 2, Pergamon Press (1977), pp. 155-162.

stead of the wings to minimize boiloff losses as well as because of their large size.

The greater volume of cryogen necessary for payload and range performance equivalent to that for conventional fuels would require a larger fuselage. However, the gross weight, and hence energy consumption, of large long-range aircraft using cryogenic fuels, particularly hydrogen, may be less than those using conventional fuels because of their greater energy content per unit weight. The weight and vaporization losses associated with cryogens lower and even reverse this energy advantage for small short-range aircraft.



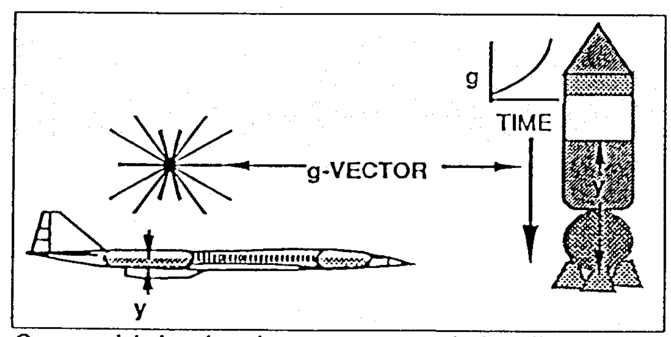
Methane and hydrogen must be stored in the body of aircraft.



Aircraft fueled with cryogens are not necessarily more efficient than those using conventional jet fuel.

The complex nature of the thermodynamic processes associated with the storage and use of cryogens in commercial aircraft offers many challenges for the design of a fuel delivery system. For the fuel system to behave in a stable manner, the fuel storage and pumping system must be designed as a unit. Insulation must be sized to minimize vaporized fuel losses and at the same time ensure the satisfaction of inlet pressure requirements of a pump that must deliver fuel over a wide range of flow rates.

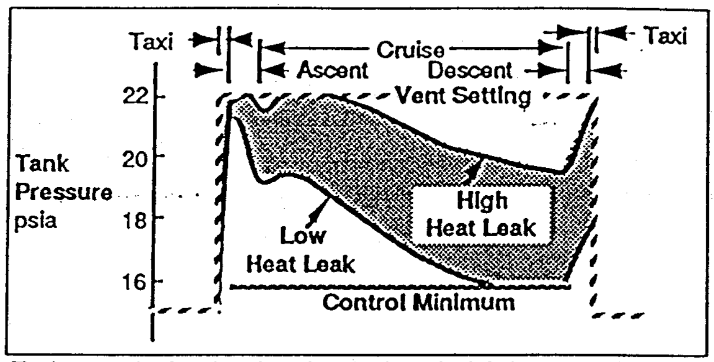
The pumping of cryogens in space vehicles is state of the art. However, space vehicle flow rates vary over a relatively narrow range and pump life requirements are counted in seconds; cost is a secondary consideration. In addition, the acceleration vector of a space vehicle is directed toward the pump inlet and increases as the fuel is used; thus the pump has at least some effective liquid head for sub-cooling. The acceleration vector of an aircraft is somewhat random and cannot be used to satisfy pump inlet pressure requirements. Helium is the



Commercial aircraft and space program mission, life, cost, and performance requirements are not compatible.

only pressurant available for hydrogen tanks and it is too expensive for commercial aircraft operations. Nitrogen can be used with methane but the solubility of nitrogen in liquid methane is a problem. Without inert gas pressurization, no existing pump can satisfy commercial aircraft weight, life, and delivery requirements. The development of such pumps will require a significant extension of existing technology or, preferably, some imaginative approaches to the transfer of hydrogen from tanks to engines.

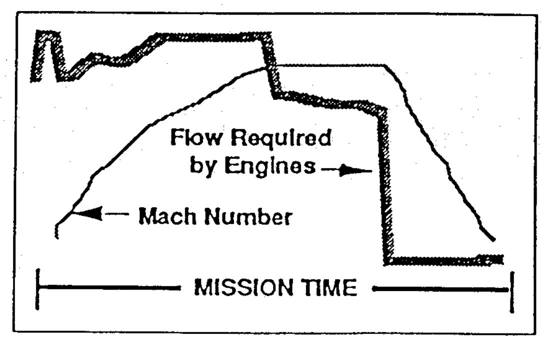
Unlike conventional-fueled aircraft, in a cryogen-fueled aircraft the duty cycle — the demand for fuel during taxi, takeoff, cruise, and descent — will play an important part in establishing fuel system concept feasibility. Analyses of system performance must account for realistic aircraft mission duty cycles before fuel system thermal protection requirements or the practical use of the cryogen as a coolant can be established.



Tanks must be insulated so that the heat leak is low enough to minimize vaporized fuel losses and high enough to prevent the pressure from dropping to where unstable liquid boiling occurs.

Currently there is no workable insulation concept for commercial aircraft fuel systems. Vacuum jackets are too heavy or delicate and currently available foam insulation cannot withstand the imposed temperature variations without unacceptable repair and inspection operations. At this point, it is not even clear how much insulation is required. Having too little insulation results in venting, and hence loss, of fuel, particularly during the taxi phases of operation. Too much insulation can cause the tank pressure to drop to the saturation point of the liquid, which can cause unstable system operation or pump cavitation. In any case, the sizing of insulation must satisfy all mission phases — taxi, ascent, cruise, and descent.

A selling point for cryogens has been their potential for use as the coolant for high-speed aircraft engines and structure. The ability to take advantage of a significant percentage of this cooling capacity in a practical commercial aircraft may prove to be quite difficult. The use of fuel cooling requires a matching of the fuel flow demanded by the engines to airframe and engine cooling requirements (a function of Mach number). Such a match has not been demonstrated for commercial aircraft.

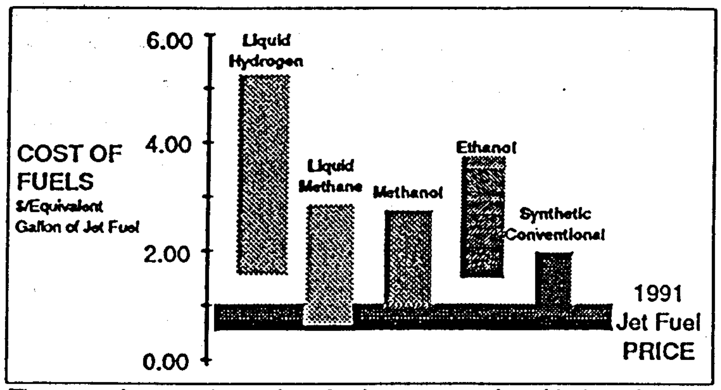


The use of cryogens to cool the structure of high-speed aircraft may not be practical.

Entirely new and more complex ground distribution and storage systems must be developed for servicing, safing, and maintaining the aircraft.[17,18] A gas liquefaction facility and fuel storage area must be located at or near the airport for safety and to limit boiloff (losses). In addition, practical commercial aircraft requirements, such as a one-hour turnaround time, will make the currently simple fueling of aircraft a relatively complex task. At the very least, the saturation pressure of the cryogen in the ground loading system must be matched to the saturation pressure of the cryogen in the aircraft tanks.

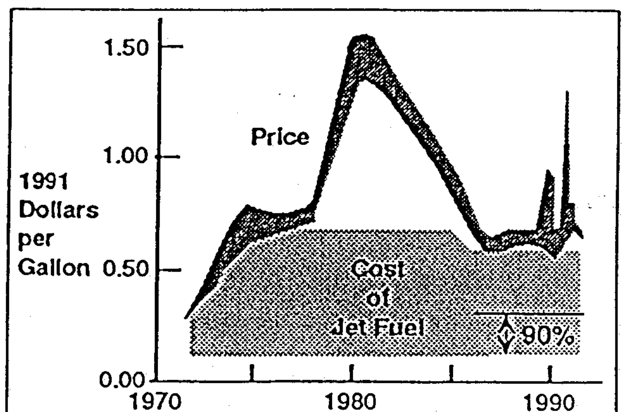
Cost and Global Warming

The cost would be enormous to develop the new airplanes and fuel handling systems required to use radically new types of aircraft fuels, such as liquid hydrogen and liquid methane.[19] Even if only the cost of fuel is considered, the most optimistic *cost* including all alternatives is at a parity with the *price* of aviation fuel derived from petroleum. However, cost does not equal price. The cost of 90% of the jet fuel currently produced is under 30¢ per gallon. This is the petroleum-based jet fuel cost that should be used in alternative fuel comparisons, not the current price. If the ground rules used in fuel comparisons are not consistent, the conclusions are meaningless.



The cost of some alternatives is close to a parity with the price of jet fuel. However, cost does not equal price.

More CO_2 is produced by the manufacture and use of most alternative fuels than by the refining and use of fuels from crude oil. The use of coal to produce hydrogen is the most environmentally unclean of the energy systems, hydrogen from water using nuclear power is the cleanest of those processes that could produce the large amounts of fuel required by aircraft. Hydrogen will become economically acceptable only after the world has exhausted its fossil fuel re-



The cost of all nonsubsidized fuels, including jet fuel, is considerably lower than price.

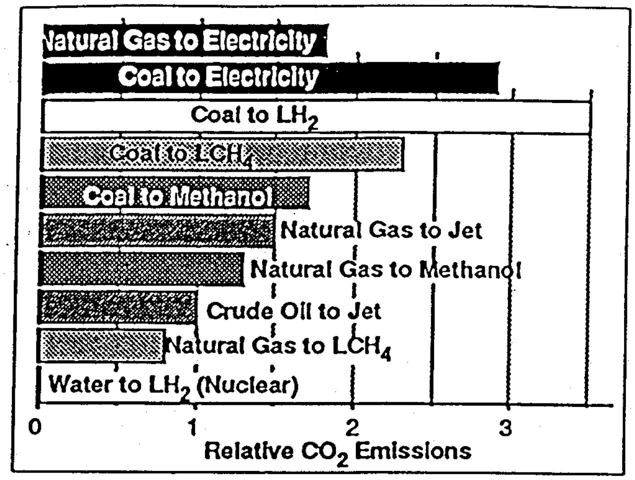
[17] The Boeing Company, "An Exploratory Study to Determine the Integrated Technological Air Transportation System Ground Requirements of Liquid-Hydrogen-Fueled Subsonic Long-Haul Civil Air Transports," NASA Contractor Report, NASA CR-2699 (September 1976).

[18] H. P. Alder, "Hydrogen in Air Transportation Feasibility Study for Zurich-Airport, Switzerland," Eidgenössisches Institut für Reaktorforschung Würenlingen Schweiz, EIR-Report No. 600 (September 1986).

[19] O. J. Hadaller and A. M. Momenthy, "Development of Fuels for Supersonic and Hypersonic Commercial Transports," Outlook for Supersonic & Hypersonic Aircraft, Transportation Research Board, Circular #333 (June 1988).

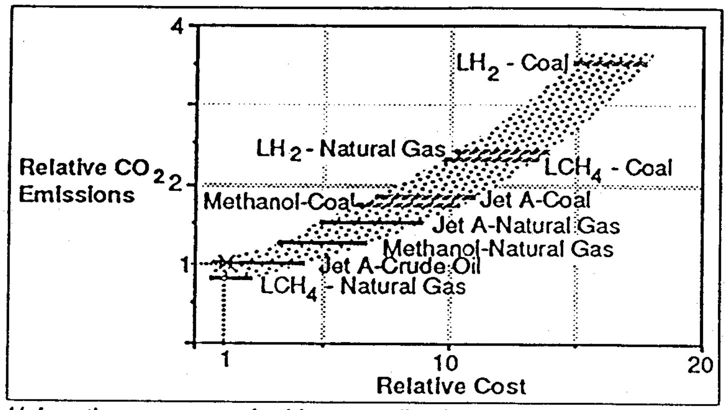
sources or a low-cost, abundantly available source of electric power, such as nuclear fusion, is developed. Without this low-cost electric power, the environmentally benign production of hydrogen from water is not possible.

Of the alternative fossil fuel options, those derived from natural gas appear to be the most environmentally benign. However, methane is also a greenhouse gas and losses from these systems would reduce their environmental advantage over other fuels.



The manufacture and use of most alternative fuels produce more CO_2 than the refining and use of fuels from crude oil.

The CO_2 produced in the upgrading of fossil fuels increases with decreasing conversion efficiency. Process energy and capital equipment costs also increase with decreasing conversion efficiency. Unless the energy required for upgrading is supplied by a non-fossil source, the production and use of most alternative fuels will increase the production of CO_2. Unless there is a real petroleum shortage or there are politically imposed costs, alternative fuels will cost more than petroleum-based fuels.



Unless the energy required for upgrading is supplied by a non-fossil source, the manufacture and use of most fuels will produce more CO_2 than those derived from petroleum.